A 100 kW three-phase plasma torch for low LHV fuel valorisation and other applications

Sabri Takali, Frédéric Fabry, Vandad-Julien Rohani, François Cauneau, Laurent Fulcheri

A 100 kW three-phase plasma torch for low LHV fuel valorisation and other applications

S. TAKALI, F. FABRY, V. ROHANI, F. CAUNEAU, L. FULCHERI
MINES ParisTech, Centre PERSEE, Rue Claude Daunesse, CS 10207, 06904 Sophia Antipolis, France,
Phone: +33.493.957.540. E-mail: sabri.takali@mines-paristech.fr.

Abstract. High density power supply is valuable in great number of industrial applications such as material processing and lean mixtures combustion enhancement. The most common technology used for these applications is actually fossil fuel burner, a process known for its limited efficiency and high operating expenses. Another alternative consists in plasma torches and in particular those with three phase current supply. In addition to its instantaneous response, security of use and low cost maintenance, Three-phase Arc Torch (TAT) with graphite electrodes is able to provide high efficiency thermal conversion and deliver dense radical formation at high temperature.

In this paper, the development of a new 100 kW plasma torch with graphite electrodes is detailed. This plasma torch is working with atmospheric air as plasma gas and has three-phase current supply at 680 Hz. The nominal air flow rate is at 60 $Nm^3.h^{-1}$ and the gas outlet temperature is above 2500 K.

At the beginning, graphite electrodes erosion by oxidizing medium was studied and controlling parameters were identified through parametric set of experiments and then tuned for optimal electrodes life. Then, a new concept respecting specifications aiming at erosion reduction, power increasing and heat efficiency enhancement was modelled and simulated on ANSYS platform for accurate results and concept validation. Here, multiple assumptions have been taken for the CFD Fluent simulation concerning plasma radiation [1] and arc discharge modelling [2]. We expose hereafter, the characteristics of the plasma flow and its interaction with the environing elements of the torch. The following step consisted in developing a detailed mechanical design respecting a close reproduction of theoretical boundary conditions.

1. Introduction

Plasma assisted combustion has a wide range of applications from low heating value fuel burner to start-ups and stabilisation in coal thermal plants. Its principle is mainly based on thermochemical activation of the combustion. At chemical level, the plasma accelerates reaction kinetics and enhances the production of highly reactive radicals and ionised species such as atomic oxygen. At a thermal level, plasma torches can deliver an important volumetric density of energy with very high efficiency. Actually, the majority of thermal plasma torches are based on DC technology which suffers from reliability problems when operating with air, need costly maintenance and uses non consumable electrodes. At center PERSEE a new plasma torche is being developed based on years of know-how in the domain of three phase plasma torches for different application domains like syngas production or black carbon nucleation.

For the development of a more powerful three phase plasma torch working in air and with electrode graphite, tests are performed on previous generation of torches to identify the main amelioration axes. Actually, the existing torches are mainly working with non-oxidizing gas such as hydrogen, argon, helium and methane. So, the first step will consist in studying the graphite electrodes erosion in air in order to find the key parameters that can lead to erosion reduction. Furthermore, since we are aiming at increasing the total power, arc discharge phenomenon is also investigated in order to reach 100 kW with minimal heat losses.

2. Preliminary study

The first test campaign is conducted to evaluate the electrode erosion at different operating conditions: with non-oxidizing gas, in air, and with a mixture of air and carbon black. In fact, the idea of injecting carbon elements with air consists in providing an alternative oxidizer for oxygen to react with instead of oxidizing electrode graphite. The test results are summarized in Tableau *1*. These tests were performed at 200 A, the electric power reaches approximately 30 kW, with a total gas flow of 5.6 $Nm^3.h^{-1}$. The first test was completed with nitrogen. If we neglect the formation of cyanid molecules (C-N) that occurs only at temperatures exceeding 3000 K [3], nitrogen could be supposed chemically neutral in presence of atomic carbon. Consequently, the eroded mass with nitrogen is mainly due to the electric discharge. In fact, under the effect of the temperature, the graphite sublimate at the cathode and anode spots. Arc roots are also under the effect of ionic and electronic bombardment [4]. In presence of air, erosion by chemical reaction between oxygen and graphite is added to the previous erosion. *Figure 1* shows the impact of both types of erosion: arc discharge effect is seen through impacts with shape of craters and oxygen erosion is noticed on the lateral surface of each electrode.

The simulation of thermodynamic equilibrium of C, O2, and N2 mixtures between 273 K and 5000 K gives the proportions of all species that can coexist as a function of the temperature. When oxygen is in excess, it reacts with all carbon atoms to form CO2 until 2000 K which dissociates then to atomic oxygen and CO. Yet, when carbon is more preponderate, it reacts with oxygen to produce CO2 until 700 K and then dissociates to give place to CO without residual atomic oxygen. It is this situation that we want to reproduce in the inter-electrode zone by injecting carbon black at very small granulometry in order to enhance CO formation and avoid the reaction between oxygen and graphite electrodes. Test results with CO as plasma gas shows the pertinence of the idea. However, Tableau *1* shows that contrarily to what one would expect, increasing the C/O ratio leads to an increase of electrode erosion. A previous study of carbon black radiation in a plasma torch [5] shows that this particle behaves like a thermal shield near the walls by absorbing the heat in the plasma zone leading to a decrease in wall heat losses. It is then possible that increasing the quantity of carbon particle for the same amount of energy, and for a very short resident time, concentrates more the energy in the discharge zone without reaching sublimation temperature to react with air. Consequently, the temperature rises and the impact of air and discharge erosions is higher.

Inlet plasma gas	Equivalent electrode life time in hours
Nitrogen	8,07
Air	2.80
Carbon monoxide	17,64
Mixture of air and solid carbon black (C/O=1)	2,81
Mixture of air and solid carbon black (C/O=1,15)	1,64
Mixture of air and solid carbon black (C/O=1,38)	1,60
Mixture of air and solid carbon black (C/O=1,75)	1,28

Tableau 1: Equivalent electrode life time in hours for a 0.12m electrode as a function of injected gas. The equivalent electrode life is deduced from the equivalent eroded length calculated from the actual eroded mass as if the erosion takes place homogenously in the transversal section of the electrode.

Figure 1: Top view of the discharge zone, the three electrodes are in planar position.

Another parameter is found to be critical for electrode erosion consists of air velocity impacting the lateral surface of the electrodes. In *Figure 2* is plotted the life length of the same electrodes from different tests conducted at different air inlet velocity. Here we see that by simply reducing the air speed at the inter-electrode zone the erosion decreases drastically. This solution is kept for future design. In addition, a protecting nitrogen layer could be injected at minimum quantity around the electrode for better protection of the electrodes.

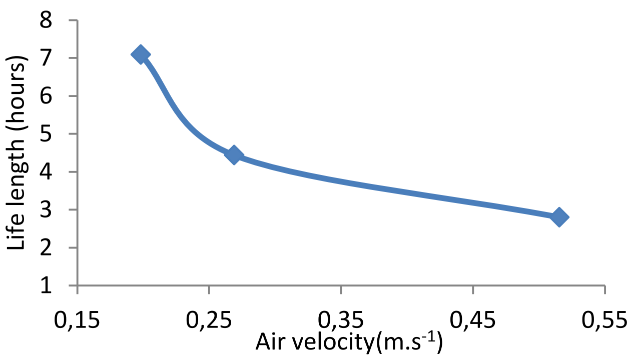

Figure 2: Graphite electrode life time as a function of air velocity in a planar three phase plasma torch.

In order to increase the power of the torch we refer to the work of C. Rehmet [3] investigating arc behaviour in three phase plasma torch. It is concluded that the impact of Lorentz force is so significant that it changes the amount of power that could be extracted by the arc for the same imposed current. In fact, the initial direction of the electrode jets determines the nature of the magnetic force. For instance in a planar electrode configuration Lorentz force has a little impact on the arc column whereas in an angular configuration this force increases and deviates the arc column stretching it outside the inter-electrode zone. Our choice for a 20° to the vertical electrode position is concluded from these observations. For technical reasons, mainly linked to plasma ignition, it is very difficult to have parallel electrodes although simulation shows it is the best configuration for maximum arc power [3].

For assisted plasma combustion the gas at the outlet of the torche should reach a temperature high enough to provide radicals for the burner. A temperature range between 2500 and 3000 K is a compromise between the low limit of oxygen dissociation [3] and the upper limit of material resistance. If the torche power reaches 100 kW with 70% thermal efficiency the inlet flow needed to obtain a minimum of 2500 K is about 0.02 kg.s^{-1} which gives an energy density of 1.11 kWh.Nm-3. The exhaust diameter has to be less than 0.15 m of diameter to obtain an outlet speed of 10 m.s-1.

3. Simulations

The objective of this simulation is the prediction of the plasma flow behaviour, the quantification of heat losses to the walls and the validation of thermal resistance of surrounding elements inside the torch. In order to obtain viable results yet inexpensive calculation cost, some assumptions are made and simplifications are suggested. First of all, the arc column is represented with a constant volume having the shape of a tore where the power of 100 kW is injected. The electromagnetic effect is neglected and supposed confined in the source volume. A parametric study is performed for the volume of this power source to seize its effect. The system is water cooled and the cooling circuit is included in the model to predict the rise of water temperature since this parameter is critical at laboratory level. Consequently the model includes two fluid zones: air as a plasma gas with a total flow of 0.02 $kg.s^{-1}$ and water at 0.277 $kg.s^{-1}$. The torch contains three graphite electrode with 0.025 m diameter able to resist to a current value up to 400 A, an electric insulation of Boron Nitride and a thermal protection made of ceramic. The different geometric shapes are simplified for simulation.

Second, we neglect the effect of gas radiation although it may represent up to 25% of the heat transfer from the electric arc [5]. Consequently, a security coefficient should be added for material dimensioning. In addition, the Local Thermal Equilibrium is assumed and the gas is supposed mono-atomic. The gas is also supposed incompressible. To represent turbulence the k-epsilon model is the most common and better suited for the gas velocity we predict [6].

The geometry, meshing and simulation are all performed on ANSYS platform. The meshing is lightened using inflations and surface dimensioning and the total node number is 375000 with a maximal node distance of 0.005 m (Figure *3*). The solving tool is Fluent which uses for this particular case the pressure based solver that solves the following Navier-Stokes equations:

Mass conservation equation: $$\frac{\partial \rho}{\partial t} + div(\rho \vec{V}) = 0 \quad (1)$$

Momentum conservation equation: $$\rho \frac{\partial \vec{V}}{\partial t} + div\, \rho \vec{V} \times \vec{V} + \overrightarrow{grad}\, p - \overrightarrow{div}\, \bar{\bar{\tau}} - \rho g^{*} = 0 \quad (2)$$

Energy conservation equation: $$\frac{\partial \rho h}{\partial t} + div\, \rho \vec{V} h + div\left(\frac{\lambda}{C_p} \overrightarrow{grad}\, h\right) - \rho g^{*} = 0 \quad (3)$$

Figure 3: Meshing of the simplified geometry (right: cross section in the middle plane, left: exterior meshing)

Figure *4* shows the gas expansion from the power source into the surrounding volume. The temperature reaches almost 7600 K inside the power source representing arc column and decreases with very high gradient to 1000 K in almost 0.03m. The gas accelerates inside the hot zone to a maximum of 50 $m.s^{-1}$ due to gas expansion. Nearby the power volume, one can notice that the high energy content creates an important pressure gradient that aspires the air into the volume and forms vortices around the arc column. The ceramic element plays its role as a temperature shield and protects the steel walls from overheating by confining the gas expansion into the outlet and its maximum temperature is about 2000 K; 400 K less than its top operating limit. The heat losses to the walls are negligible and this is mainly due to the absence of radiation. This leads to higher outlet averaged temperature of about 4000 K. The electric insulation element is not also overheating although the proximity of the power source. The air layer passing between the ceramic and steel walls plays also its role in cooling the ceramic and avoiding the conduction of heat if they were in contact. The current lines from the gas inlets show no backflow in the exhaust but some recirculation pockets are created at the vicinity of the walls which may disturb arc discharge. The mass weighted average of molecular viscosity, density and velocity at the outlet are successively: 0.000115 $kg.m^{-1}.s^{-1}$, 12.2 $m.s^{-1}$ and 0.155 $kg.m^{-3}$, and knowing that the outlet diameter is 0.15 m, the Reynolds number is 2466. This means that the flow is not laminar and starts passing to turbulent state.

At the frontier between cold and hot gas where the temperature gradient is high, Prandtl number (Figure *5*) reaches the value of 0.8 showing that thermal diffusion governed by the gas conduction and its specific heat capacity becomes as strong as the viscous diffusion characterised by the cinematic viscosity whereas inside and outside the plasma thermal diffusion dominates. This means that this gas layer with high temperature gradient and high Prandtl number behaves more like a barrier that brakes the cold gas. The penetration of inlet air into the plasma is more occurring because of the depression. On should expect that hot and cold gas would not mix easily.

The thermal conductivity, the specific heat capacity and the dynamic viscosity all have approximately the same field distribution and increase with the temperature except in the hottest zone where we see the non linearity of these characteristics.

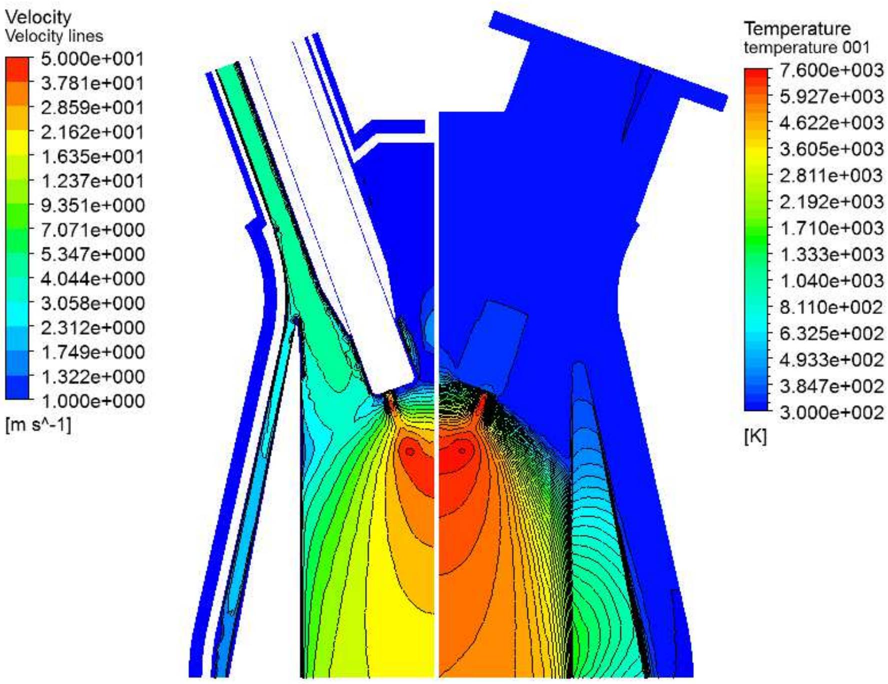

Figure 4: Temperature (right) and velocity (left) fields across the middle plan.

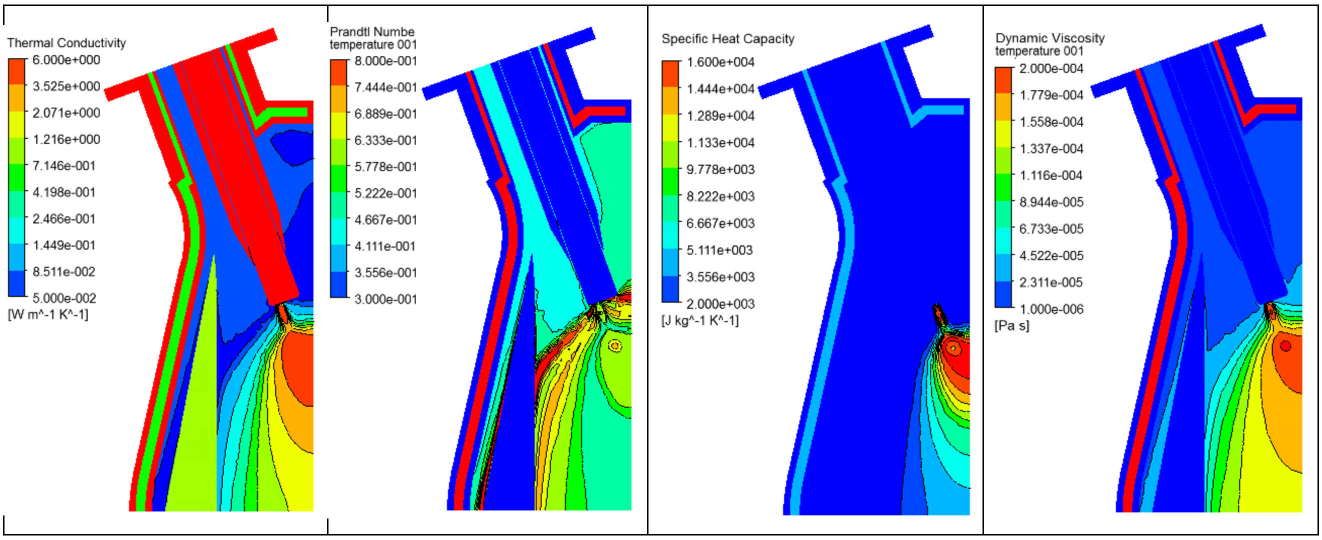

Figure 5: Thermal conductivity, Prandtl number, specific heat capacity and dynamic viscosity fields

4. Conclusion

The validation of the plasma flow and thermal resistance of the different components of the 100 kW torch led to the detailed mechanical design respecting mounting, tuning and manufacturing constraints. Besides, the gas inlets was conceived to respect inlet condition as suggested in the model. The ceramic element was tested at equivalent thermal stress and then molded according to simulation shape. After the new design was manufactured, the new torch has been mounted on test bench and the first start up test was successful and showed up to 80% heat efficiency. A series of test campaigns is now programmed for reliability validation and characterization of this torch. Through this experiment, heat losses, electric characteristics, electrode erosion, wall temperatures and overall efficiency will be carefully evaluated. In addition, for better understanding of the plasma flow, more accurate simulations that takes into account radiation will be performed.

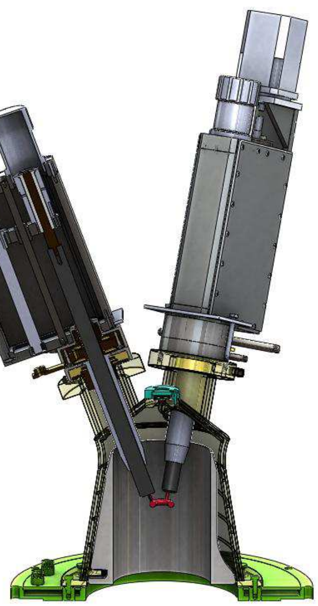

Figure 6: Design cross-section of the 100 kW three-phase plasma torch.

Figure 7: Shot of the 100 kW torch mounted after manufacturing

References

[1] H. RIAD, Calcul du transfert radiatif dans des arcs et des plasmas thermiques: Application au méthane et à l'hydrogène, Thèse. Université Paul Sabatier (1996)

[2] C. REHMET, 2013 "3D unsteady state MHD modeling of a 3-phase AC hot graphite electrodes plasma torch", Plasma Chemistry and Plasma Processing, April 2013, Volume 33, Issue 2, pp 491-51, (2013)

[3] G. Flamant, J.M. Badie, Les Plasmas thermiques, Institut de Science et de Génie des Materiaux et Procédés, CNRS, (1995- 1996)

[4] L'arc électrique et ses applications T.1, ISBN-10: 222203535X, CNRS Edition, (1984)

[5] I. DEME, Contribution à la modélisation de l'écoulement dans un réacteur plasma pour la fabrication de noirs de carbone. Influence du rayonnement des particules de carbone. Thèses. Ecole Nationale Supérieure des Mines de Paris, (2002)

[6] Zhou Q, Li H, Xu X, Liu F, Guo S, Chang X, Xu P (2009) Comparative study of turbulence models on highly constricted plasma cutting arc. J Phys D Appl Phys 42:015210